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Performance Analysis of Foam Agents Required to Combat Liquid Fuel Hazards

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14. ABSTRACT

This paper presents a framework for determining the required fire extinguishment and burnback performance of fire fighting foam on Class B fires. A generalized method to assess performance is presented and applied to a Navy aircraft carrier flight deck. For the hazards involved in the flight deck, fire extinguishing agents must control/extinguish fires in 30 to 90 seconds to prevent the onset of critical thresholds (e.g., ordnance cook-off). Current systems utilizing MIL SPEC AFFF meet this requirement. If MIL SPEC AFFF is eliminated, e.g., because of environmental concerns, it will be difficult to meet this performance using available alternative agents/systems.

There is a correlation between the MIL SPEC AFFF test method/criteria and large-scale pool fire extinguishment performance; the small-scale MIL SPEC test method provides a factor of safety in terms of extinguishment performance. Any efforts to change the performance characteristics of the MIL SPEC should proceed with extreme caution. The MIL SPEC tests provide a reasonable screen method for alternative agents. Intermediate scale tests may have to be used for novel agents.

15. SUBJECT TERMS

Fire fighting foam, MIL SPEC AFFF, fire extinguishment, hydrocarbon fuels, small and large-scale tests, hazard assessment, aircraft carriers, Navy fire protection

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PERFORMANCE ANALYSIS OF FOAM AGENTS REQUIRED TO COMBAT LIQUID FUEL HAZARDS

1.0   INTRODUCTION

Different foam formulations are or could become available where the use of film-forming foam is potentially restricted. Alternative foam formulations have different levels of fire extinguishment and burnback performance. The intent of this paper is to present a framework for determining "how good is good enough" in terms of foam agent performance. The focus is on the required fire extinguishing performance. An example for aviation fire protection is presented, specifically an incident on a U.S. Navy aircraft carrier flight deck. The methodology can be readily adapted to any military or commercial fuel hazard application. The objectives of this analysis are to:

1. Present a generalized methodology which can be used to assess the fire performance requirements of a foam agent needed for rapid hydrocarbon pool fire extinguishment;
2. Apply the generalized methodology to a Navy fire hazard, specifically the flight deck of an aircraft carrier;
3. Identify the correlation between the large-scale fire performance required to meet the threat, and current standardized reduced/small-scale testing; and,
4. Make a preliminary determination whether foam fire-extinguishing performance and associated screening qualification techniques require modification in the context of assessing environmentally improved foams.

2.0   APPROACH

A "systems" approach was used to evaluate liquid fuel hazards associated with Navy assets. A systems approach is used to:

1. Identify threats/hazards;
2. Determine the desired or appropriate level of protection for the threat;
3. Identify means to achieve the desired level of protection; and
4. Evaluate/rank alternatives for providing the level of protection.

This approach is used in lieu of a "drop-in" approach, which assumes the current level of performance/protection for a given hazard is appropriate and non-negotiable in terms of risk/cost benefit. This leads to an approach where direct chemical alteration of existing agents is immediately assessed so that existing equipment can be utilized. This approach inherently assumes a cost/benefit relationship favoring the use of existing equipment at the potential expense of fire and/or environmental performance.

Using the systems analysis, Items 1-3 were quantitatively addressed in the context of Navy aviation fire protection. This paper does not address alternatives to achieve the desired level of protection, since this requires policy-level decision making. Likewise, it is also premature to rank

alternatives, because this involves identification of appropriate agent environmental criteria plus engineering cost/benefit trade-off analysis. It is assumed that these evaluations would be conducted in the future based on proposed new agents.

3.0   GENERALIZED PERFORMANCE ANALYSIS

The performance methodology outlined in this paper was developed for military aviation hazards during Halon replacement efforts [1]. It has been effectively applied to Navy shoreside aircraft hangars to identify the level of suppression and detection system performance required to protect parked aircraft [2]. The initial step is to perform a Fire Hazard Analysis (FHA).

This includes the following steps:

1. Plausible fire scenarios must be identified and assessed in terms of thermal and toxic characteristics;
2. Consequences (including thresholds) must be calculated. This includes calculating the impact of fire on personnel and equipment; and
3. Based on the calculated impact, appropriate critical thresholds can be proposed and adopted. Exceeding the critical thresholds results in unacceptable damage or injury. If desired, risk-based methodologies can be used to identify the sensitivity of variables in establishing impacts and critical thresholds.

Timelines are then developed to determine when critical thresholds are exceeded. They are also used to evaluate methods to prevent onset of critical damage. The fundamental time to prevent critical damage or personal injury is given by Equation (1):

$$Time_{Fire\ Control/Extinguish} < Time_{Critical\ Threshold} \qquad (1)$$

For a "system" protecting a liquid fuel hazard to be "successful," i.e., prevent critical damage or limit effects to personnel, $t_{Fire\ Control/Extinguish}$ must include the actuation and operation times of the system as shown in Equation (2):

$$t_{Firecontrol/extinguish} = t_{Detect} = t_{Systerm\ Operation} + t_{Agent\ Control/Extinguish} \qquad (2)$$

Substituting Equation 1 in Equation 2 results in:

$$t_{Detect} + t_{System\ Operation} + t_{Agent\ Control/Extinguish} < t_{Critical\ Threshold} \qquad (3)$$

Prior to applying the generalized assessment to a specific hazard, a preliminary evaluation of Navy liquid fuel hazards protected by AFFF was performed. The priority was established relative to the need for rapid pool extinguishment. The results are shown in Table 1. The aircraft carrier flight deck scenario was identified as the highest priority. This is based on the potential for weapons cook-off and a multi-plane incident, the susceptibility of the ship to battle damage, and the monetary and strategic value of the asset. This application was selected for detailed evaluation.

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4.0   AIRCRAFT CARRIER FLIGHT DECK HAZARD EVALUATION – BASELINE SCENARIO

Hazards associated with the flight deck were identified. These include: ordnance stored on aircraft and staged outboard of the island structure (bomb farm [3]); fueled aircraft and fueling stations at catwalks; high value aircraft, potentially parked in close proximity; and, proximity of the island structure which includes personnel and mission-readiness issues. Peacetime and wartime scenarios were considered. An example of a peacetime incident is an aircraft crash during flight operations, or the accidental firing of ordnance.

Table 1. U.S. Navy Prioritized AFFF Applications (Preliminary)

Application	Relative Priority *	Rationale for Assigned Priority
Ship – Aircraft Carrier Flight Deck	1	- Weapons cook-off potential - Need for occupant rescue - Greatest potential for immediate multi-plane incident due to crash into pack of aircraft - Minimal separation distances between aircraft, between ordnance items, and between aircraft and ordnance - Proximity of threat area to occupied areas - High value asset - Potential for battle damage
Ship – Helicopter Flight Deck	2	- Same as flight deck, but: - Less potential for multi-plane incident - Lower parking density (greater separation distances) - Lesser amounts of ordnance
Ship – Aircraft Carrier Hangar	2	Same threat as flight deck, but less probability for sudden multi-plane incident and less ordnance
Ship – Amphib Well Deck	2	Large volume storage, including potential for ordnance and gasoline
Ship – Helicopter Hangar on Large Deck Amphib	3	Less ordnance relative to aircraft carrier hangar
Ship – Single Helo Hangar on Small Ship	4	Single aircraft - Minimal ordnance - Negligible life safety threat
Ship – Machinery spaces	3	High value asset, but no ordnance exposure AFFF has minimal impact on life safety threat due to presence of other total flooding agents
Shore – Crash firefighting/rescue Apparatus	2	- Need for occupant rescue - Weapon cook-off potential
Shore – Aircraft Hangar	2	- Concentration of high value assets
Shore – Hot Refueling Stations	2	- Need for occupant rescue - Weapons cook-off threat
Shore – Hush Houses, Fuel Farms, Structural Pumpers	4	- Physically separated assets - Minimal life safety threat

* Priority relative to need for rapid pool fire extinguishment

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Peacetime catastrophes have occurred [4]. Wartime scenarios include an aircraft crash during flight ops or battle-induced damage. The scenario selected for evaluation is an aircraft crash in peacetime or wartime or a "survivable" battle-induced flight deck fire involving aircraft, ordnance, and liquid fuel. All of these scenarios essentially involve the same hazards and associated timelines, with the variable being the total area of involvement.

The baseline scenario involves an initial incident where an aircraft crash results in a JP-5 fuel fire, both 2- and 3-dimensional. There is a massive amount of debris and fires may be shielded by damaged aircraft [4,5]. Ordnance may or may not be the initiating event depending on the scenario; both situations have actually occurred.

The primary fire threat, from an AFFF protection standpoint, is the resulting liquid pool fire threat. Before consequences are estimated, the characteristics of the pool fire threat must be established. The ignition and fire growth potential of aviation fuels has been well documented. The Navy uses JP-5 for ship-based aviation, while JP-8 is used for shore operations. In the past, there have been situations where more hazardous fuel (e.g., lower flashpoint JP-4) could be used on the flight deck. This was particularly true when the U.S. Air Force used JP-4. They have subsequently changed to JP-8. An assessment of the reduction in hazard between JP-4 and JP-5/8 has been performed [6]. The USAF found that:

1. JP-8 and JP-5 must be subjected to a sustained high-energy heat source in order to produce the vapors required for ignition;
2. The flame spread rate of JP-4 is 20 times greater than that of JP-8;
3. Flame spread rate determines how long after fuel ignition that a JP-fuel fire becomes hazardous to adjacent equipment and structures. The difference in flame spread rate allows more time for personnel, a suppression system, or firefighters to respond to a JP-8 or JP-5 fire; and
4. There is no prominent difference in the fire intensity of JP-4, JP-8 and JP-5.

The USAF concluded that even though JP-8 provides greater fire safety than JP-4, it is prudent to determine the most cost-effective intervention method should an inadvertent or accidental fire occur.

The elimination of the potential for JP-4 to be mixed with JP-5 on an aircraft carrier flight deck certainly reduces the fire hazard. The potential still exists for JP-8 to be mixed with JP-5. There are situations where this mixed fuel may be exposed to high ambient heat (i.e., Persian Gulf operations). A study of the ignition and flame spread of mixed fuels (JP-5/JP-8) has been performed [7]. The Naval Research Laboratory (NRL) reported on the following characteristics:

1. Flashpoint – The lowering of the flash point of the JP-5 was nearly directly proportional to the amount of JP-8 added. To the extent that the flash point is lowered, the ignition hazard is increased (this is not true for JP-4 mixtures with JP5/8, where small amounts of JP-4 in JP-5 or JP-8 reduce the flash point precipitously [7,8]);
2. Flame spread – Up to about 11 °C (20 °F) above the flash point, the flame spread rates for all fuels were similar, increasing gradually with temperature. Above this temperature, the flame spread rates continued to increase: the flame spread rate for JP-8 eventually reached about 150 cm/s (60 in./s); and
3. In a worst-case scenario, the flame spread rate for JP-8 was twice as fast as JP-5, indicating the flight deck personnel would have up to twice as long to react to an advancing fire if the fuel were JP-5 instead of JP-8; this difference is measured in seconds.

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NRL concluded that, in certain scenarios, fires involving JP-8 could be more difficult to extinguish than the same scenario involving JP-5.

It must be recognized that the fire hazard is not limited to a pool fire scenario. In an aircraft crash resulting in traumatic rupture of a fuel tank, fuel may be released as a mist or aerosol. In this case, JP-5 can exhibit ease-of-ignition characteristics similar to fuel vapors. Also, a gravity fed three-dimensional fire may result from a leak, ruptured tank, or multiple ruptured tanks. Currently, these threats are handled by "secondary" agents such as dry chemicals (PKP) and gaseous agents.

For purposes of the fire hazard assessment, it was assumed that the fire scenario included: a pool of fuel involving a large area of the flight deck; immediate ignition of the pool; nearly immediate flame spread over the pool (worst-case – no delay for full fire involvement was assumed); the potential for a deep-seated, obstructed, difficult to access fire due to debris; the potential for a running fuel fire(s) from "gashed" fuel tank(s) (non-pressurized); and ordnance within the incident area or in close proximity.

5.0   CONSEQUENCES

Thermal radiation calculations can be used to estimate the impact of a pool fire exposure on personnel, equipment, and materials. Thermal radiation to an item or "target" seeing the flame is calculated using the fundamental heat transfer for equation (4):

$$Q = \varepsilon \cdot \sigma \cdot \phi \cdot T^4 \tag{4}$$

where Q = heat flux (kW)
        ε = flame emmisivity (dimensionless)
        σ = Stefan-Bolzmann constant, 56.7×10^{-12} kW/m °K
        ϕ = view factor
        T = flame temperature (°K)

Considerable work has been performed to simplify the calculation of heat transfer from pool fires to targets. Variables include fuel characteristics, burning rate, flame height, distance to a target, wind affects, and complicated view factors. A review of this data is available in the literature. For example, a commonly used correlation has been published by the Society of Fire Protection Engineers [9]:

$$\dot{q} = 15.4 \left(\frac{L}{D} \right)^{-1.54} \left[\frac{kW}{m^2} \right] \tag{5}$$

where $\dot{q}$ = heat flux to a target (kW/m²)
        D   = diameter of pool fire (m)
        L   = distance from the center of the pool fire to the edge of a target (m)

"Targets" include personnel, aircraft, ordnance, and the ship structure. They may be immersed in flame or may be at some distance from the edge of a burning pool. The assumption of an immersed target is the more conservative approach; direct flame exposure is assumed for this analysis. Assuming an immersed target, the impact of the fire on personnel, ordnance, and aircraft can be assessed with no allowance made for flame spread across a pool.

5.1   Life Safety

Personnel exposed to a pool fire will be effected when the incident thermal flux exceeds the flux which causes burn injuries. Prevention of burn injuries can be expressed by:

$$Q_{Incident} < Q_{Thermal\ burn} \tag{6}$$

The time to burn injuries is a function of the incident flux and the duration of the exposure as shown in Figure 1. This is incident flux to bare skin. Factors include the proximity of the pool fire to personnel and the aircraft fuselage integrity/thermal resistance. If the fuselage is intact, the rationale for the critical time for life safety used in civilian aviation provides a reasonable first-cut estimate. Burn-through of the fuselage occurs in 1-3 minutes, followed quickly by serious injury due to the thermal insult [10,11]. If the fuselage is not intact, the time to critical burn could be much less that one minute. Since the incident heat flux could be 50-100 kW/m^2, burn injuries could occur in seconds as shown in Figure 1. This is a somewhat conservative estimate, since the pilot will likely have some protection from a flight suit and helmet. Summarizing, under worst case conditions, the critical threshold for personnel life safety could be less than 30 seconds. In this case, the ability to perform rescue operations is very difficult (i.e., the pilot is engulfed in the fire instantly). A more reasonable design criteria is a critical threshold of 1-2 minutes, which assumes some minimal time for fire development and some nominal protection of the pilot by a flight suit.

5.2   Ordnance Cook-off

The general heat transfer methodology can be used to calculate incident flux to ordnance exposed to fire. Ordnance will explode or "cook-off" when the energetics reach a critical temperature or when heating results in a self-reaction process even after the heat source is removed. Missile rocket motors can have self-oxidizing material, and may also "cook-off." Considerable research has been performed in this area. In previous fire testing, two simplified criteria have been used [5]:

1.   The ordnance inside case temperature exceeds 650 °F; or,
2.   The temperature rise after cooling operations have commenced exceeds 150 °F.

These criteria have been further simplified for firefighting doctrine and tactics purposes. The characteristics of air-launched weapons (rockets, bombs, and missiles) have been characterized in terms of the time at which a major firefighting hazard occurs [12]. These times range from 40 seconds to nine minutes. Five devices pose a major hazard after one minute or less of fire exposure, and seven devices after two minutes of exposure.

As with the personnel hazard, the critical threshold may be less than one minute for absolute worst case conditions, i.e. immediate flame immersion of the missiles having the quickest cook-off time. Assuming there is some modest time for exposure and heat build-up/transfer to the ordnance, a reasonable threshold criteria is one-two minutes. This tracks with the personnel safety threshold criteria.

5.3   Aircraft

Aluminum and composite aircraft can be damaged by relatively modest thermal insults. The impact of fires to U.S. Air Force aircraft has been previously analyzed [1]. It is expected that Naval aircraft exhibit similar responses to fire. Aluminum structural failure occurs at 100-150 °C. Aircraft composites are stable up to about 200 °C. Maximum structural loss occurs in the 350-490 °C range [13].

A detailed analysis of critical thresholds would include proximity of aircraft to the incident. The generalized techniques in Equation (5) is used to calculate this impact with the critical aluminum or composite damage temperatures translated to an equivalent heat flux. For preliminary purposes, the same assumptions used for personnel safety and fast ordnance cook-off can be made. Aircraft intimately involved in the initiating incident may fail in less than one minute, but are probably already structurally damaged due to the impact of the initiating incident. Time to reach critical temperatures in aircraft at some distance from the fire is not expected to be less than the one-two minute times established for personnel safety and ordnance cook-off. This one-two minute critical time remains an appropriate design threshold.

5.4   Other Hazards

The analysis currently addresses the primary hazard associated with the flight decks. The impact to the ship island structure needs to be assessed in terms of mission-criticality (i.e., communications, flight operations). The island currently is protected by a water-washdown system installed for chemical-biological – radiation (CBR) protection. Hazards associated with future carrier designs, and hostile liquid fuel incendiary weapons effects, should also be considered.

5.5   Summary of Consequence Analysis

The critical threshold is one-two minutes. Fire must be controlled within this time, otherwise personnel are in jeopardy, ordnance may cook-off, or aircraft may be damaged. There are scenarios where damage/injury could occur more quickly; a cost-benefit analysis would have to be performed to determine the reasonableness of protecting against these threats. The cost to protect against these threats, if technically feasible, may be prohibitive.

6.0   REQUIRED FIREFIGHTING PERFORMANCE

The required firefighting performance of a foam agent can now be determined based on the critical threshold of one-two minutes established in the consequences analysis. Equation (3) can be rewritten to solve for the required foam agent control/extinguishment performance:

$$t_{Agent\,Control/Extinguish} < t_{Critical\,Threshold} - t_{Detect} - t_{System\,Operation} \qquad (7)$$

Detection and notification time for a flight deck conflagration is nearly instantaneous. The flush deck AFFF system protecting the flight deck of an aircraft carrier would be activated immediately when there is a fire. The flush deck system, originally installed to provide CBR water-washdown protection, has been adapted to discharge 0.06 gpm/ft^2 of AFFF. Both 1.5 and 2.5 inch diameter AFFF hoselines are available from catwalks located port and starboard of the flight deck. Also, several crash firefighting rescue (CFR) vehicles (P-25) are positioned to rapidly respond to an incident. Each can discharge 500 gpm of AFFF.

The flush deck nozzles have been designed for rapid discharge of agent. The system is "wet" to just below the flight deck, and AFFF concentrate injection points are located near the flight deck to reduce proportioning time. Initial flow from the nozzles occurs within ten seconds of system activation. Full flow occurs 15-30 seconds after activation. Catwalk 1.5 inch diameter hard rubber hose on reels can be placed in service within 30 seconds; 2.5 inch diameter soft hose takes up to 60 seconds because the hose must be flaked-out before charging. The P-25 CFR vehicles have "pump-on-the-run" capability. They can discharge AFFF to the crash within 30 seconds, provided their access is not blocked.

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Summarizing, the current AFFF systems on an aircraft carrier can be expected to deliver foam from multiple sources to a crash/ordnance incident within 30 seconds.

Substituting the critical threshold, detection, and system operating times in Equation (7), the required foam agent performance can be determined:

$$t_{Agent\ Control/Extinguish} < t_{Critical\ Threshold} - t_{Detect} - t_{System\ Operation}$$

$$t_{Agent\ Control/Extinguish} < (60\ to\ 120\ sec) - 0 - 30\ sec$$

$$t_{Agent\ Control/Extinguish} < 30\ to\ 90\ sec$$

The firefighting agent must control/extinguish a fire in 30-90 seconds to prevent critical impact to personnel and materials.

The required fire control/extinguishment performance of the agent could be changed by changing one or more of the variables affecting performance. For example, the threat could be reduced by making current aviation fuel less hazardous (i.e., increasing the flashpoint and reducing the pool flame spread rate). Similarly, the consequences could be reduced through design/procedure changes:

1. Personnel – by providing a more hardened/survivable aircraft, or providing greater personnel protection;
2. Ordnance – by designing weapons to increase cook-off times; and
3. Aircraft – by hardening aircraft to be more fire resistive.

Foam system discharge characteristics could be modified to change performance. Foam could be discharged more quickly or at a greater rate. It would be very difficult to activate the system more rapidly (i.e., it has already been optimized). Higher flow rates could be provided, but there would be a substantial costs in changing existing fixed systems to accommodate such an increase.

A quantitative assessment of modifying the variables would have to be performed to determine the feasibility of any approach. Qualitatively, there does not appear to be much promise in the near term to effect these variables. To a large extent, these systems have already been optimized; there is little promise that significant fire protection performance improvement of these systems (i.e., increased ordnance cook-off times or fire-hardening of aircraft) can be accomplished without a corresponding significant reduction in mission requirements. The required performance of a foam agent to control/extinguish a fire in 30-90 seconds is appropriate.

7.0 CORRELATION BETWEEN LARGE-SCALE POOL FIRE EXTINGUISHMENT PERFORMANCE AND REDUCED-SCALE ASSESSMENT METHODS

Foam is designed to combat large liquid pool fires. Fire extinguishment, burnback resistance, environmental and operational performance are addressed by listing/qualification testing (e.g., the U.S. Military AFFF Specification [14]). This paper focuses on extinguishment and burnback resistance.

7.1 Effectiveness of AFFF

The effectiveness of AFFF on pool fires associated with aviation hazards is well known [15]. The theory and test work is not repeated here but just summarized.

Civilian aviation requires a 0.13 gpm/ft² AFFF application rate to protect against crash fires [11]. The total flow rate and quantity of agent is based on the Practical Critical Fire Area (PCA) which is associated with the size of aircraft using a facility. Allowance is also made for interior attack hose streams. The Navy essentially uses NFPA 403 for shore based facilities. A modified approach is used for aircraft carriers, recognizing the unique hazards and limited availability of back-up resources. There is no "minimum" application rate per se. Protection includes:

1. Flush deck nozzles discharging 0.06 gpm/ft², which have the capability to control pool fires in 30 seconds. Extinguishment on the order of 60 seconds has been shown. The 0.06 gpm/ft² was adopted to include a factor of safety and address the possible use of low flash point fuels from different military services;

2. 1.5 in. hose reels and 2.5 in. AFFF handlines located in catwalks around the perimeter of the flight deck;

3. Two P-25 firefighting vehicles with 500 gpm AFFF turret nozzle capability staged near landing/takeoff areas. These vehicles are running and fully-manned during flight operations; and

4. Deck edge nozzles discharging 30 gpm each to protect the flight deck edge (protecting parked aircraft which may not be readily accessible) and the bomb farm (located outboard of the island).

Tests have demonstrated that these systems control JP-5 pool fires in approximately 30 seconds and extinguish pool fires in approximately 60 seconds. Detailed test data is available in References 3, 5, and 15-21. These times exclude shielded, difficult-to-access fires, which may include three-dimensional scenarios. These fires should be considered separately in terms of AFFF performance.

8.0   CORRELATION BETWEEN SMALL AND LARGE-SCALE TESTS

The correlation between small-scale tests (MIL SPEC tests) and large-scale performance has been shown for handline and turret application [15,17,18,19]. The results are shown in Figures 2-4. The variables investigated include: application rates between 0.02 and 0.36gpm/ft²; test areas ranging from 28 ft² to 16,000 ft²; low and high flash point fuels; and, air-aspirating or non-aspirating nozzles. A detailed analysis was performed for low flashpoint fuels (AVGAS, MOGAS, JP-4). Ninety percent control time was the measure of performance. All nozzles were included in the evaluation (air aspirating and non-air aspirating). The effects of application rate are shown in Figure 2. The same trends developed by Geyer [22] in earlier test work were identified: control times increase exponentially as application rate decreases, particularly below 0.10 gpm/ft². The 0.10 gpm/ft² is considered a "critical" application rate for rapid fire control using handlines and turrets. AFFF discharged through flush deck nozzles has been optimized to extinguish JP-5 fires at a rate of 0.04 gpm/ft². The U.S. Navy uses 0.06 gpm/ft² as design criteria for shipboard flush deck systems to account for the possible use of low flash point fuels [21].

Scaling effects are shown in Figures 3-4. The time needed to control a unit of burning area (s/ft² or s/m²), designated as the "specific control time," is plotted as a function of fire size. For low (0.03-0.06 gpm/ft²) and intermediate (0.07-0.10 gpm/ft²) application rates, the specific control times decrease linearly as a function of fire area when plotted on log-log scales. Higher specific control times are required for the MIL SPEC test fires (28 and 50 ft²) compared to large fires. This is readily apparent as actual control times for the small fires are on the same order as results from large fires [18]. Figure 3 also shows specific control time criteria which was originally proposed for the MIL SPEC. This original draft proposal included a requirement for 85 percent control in 30 seconds for a 400 ft² (37 m²) and a 1200 ft² (110 m²) fire at an application rate of 0.04 gpm/ft². These requirements were

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considered redundant based on the small- and larger-scale developmental test data. They were deleted from the MIL SPEC requirements [23].

The FAA criteria for Index A-E (NFPA 403 Category 1-10) airports is also shown in Figures 3 and 4. Using Practical Critical Control Areas for these airports and the NFPA requirement for fire control in 60 seconds, specific control time as a function of area is shown. The data indicate that specific control times with MIL SPEC products applied at less than design application rates (i.e., 0.13 gpm/ft^2) can meet control times established by NFPA and FAA requirements for extinguishment of pool fires. The limited data for AFFF which does not meet MIL SPEC requirements suggest that these agents may not meet minimum NFPA and FAA required control times when applied at less than design rates.

From these data, it was concluded that a scaling relationship exists between MIL SPEC small-scale fire tests and actual large-scale crash firefighting and rescue scenarios. The MIL SPEC tests are more challenging than the larger tests in terms of time to achieve control, but this challenging test produces an agent that can meet large-scale pool fire extinguishment at less than the recommended design application rates.

These data indicate that there is a safety factor with AFFF which passes small-scale tests (e.g., 50 ft^2 MIL SPEC MOGAS test with a 0.04 gpm/ft^2 application rate and 0.033 gal/ft^2 extinguishment density) and the extinguishment performance at large-scale. This may not be the case with other agents. This is considered important during the initial application of foam to a large spill fire, when the "effective" application rate may be much less than the critical application rate of 0.10 gpm/ft^2. New agents may not be "correlatable" using the same techniques used to correlate AFFF results (i.e., large test results compared to 28 and 50 ft^2 MIL SPEC tests). The MIL SPEC small-scale fire tests are considered appropriate to screen new agents. For novel agents which are not readily adaptable to the small-scale MIL SPEC fire tests, performance could be assessed at an intermediate scale. Fire control (90% extinguishment) in 30 seconds of a 1,000 ft^2 pool of low flashpoint fuel (gasoline or n-heptane) using a 50 gpm nozzle would be a reasonable screening method for aqueous foams. The mass flow rate of the agent could be varied to identify the lower limit to meet the 30 second control criteria.

The correlations developed for foam handline and turret operation have not been developed for low-level foam application. Attributes of low-level AFFF applications include:

1. No plume penetration is required, and there is direct application to the base of the fire. This is considered to be very important, i.e., the discharge acts more like a handline nozzle than an overhead sprinkler;
2. Foam discharged upwind of a fire is more effective than discharge in zero wind conditions. There is a "sweeping" effect associated with upwind AFFF application;
3. Non-air aspirating devices are important to success, i.e., to project the stream and limit pressure losses; and
4. Control/extinguishment times of pool fires on the order of 30-60 seconds can be achieved at application rates of 0.04-0.06 gpm/ft^2.

The low-level nozzles are "optimum" systems in that they are designed to discharge at application rates used in the MIL SPEC tests, i.e., below the "critical" rate of 0.10 gpm/ft^2. All designs have been based on large-scale experimental results; no detailed correlation has been established between large-scale and small-scale other than the use/effectiveness of the 0.06 gpm/ft^2 application rate.

9.0   ASSESSMENT OF BURNBACK PERFORMANCE

Very little data is available which quantifies a minimum level of burnback resistance for specific applications. Standards/specifications (MIL SPEC, UL) set requirements essentially on what a foam agent can achieve in the small-scale test.

The original AFFF "modeling" work by Peterson [17] provides a good analysis of the trade-off between extinguishment and burnback when comparing protein foam and AFFF. Previously, when protein foam was the primary agent for extinguishing aircraft fires, the burnback resistance or rate of foam-blanket burn-off was a common denominator in all applications. The stability or rate of water dropout (measured as 25 percent drainage time) from protein foams influences its ability to resist heat, and the burnback characteristics of protein foams varied depending on how they were made (expansion and drainage-time properties). However, these differences are small in comparison to the wide differences between types of agents. At one end of the scale is dry chemical (used as a secondary agent), which has practically a zero burnback resistance, and at the other end is protein foam, which has in general the longest burnback resistance. The decision of what agent is "best" is difficult, since the highly sought property of quick fire control has been in an opposite relationship; i.e., dry chemical is very fast and protein foam very slow. Likewise, AFFF has very rapid fire control but may have less burnback resistance compared to protein foam.

An analysis of small-scale fire test burnback performance for marine applications was conducted as shown in Table 2 [24]. Performance was assessed in terms of the quantity of foam required per unit area of fuel surface to provide one minute of burnback protection. This assessment used the total foam discharge time as the basis of foam quantity. The fire test pan size was the basis of fuel surface area. For the tests involving a sealability test before the burnback test, the time during the sealability test was included as part of the total burnback time. Interestingly, the "burnback density" (volume of foam per unit of fuel area) to provide one minute of burnback protection falls within a relatively narrow range $(0.014\text{-}0.021 \text{ gal/ft}^2 \ (0.58\text{-}0.84 \text{ L/m}^2))$ for all of the test methods. However, test method differences (preburn times, pan freeboard areas and geometry, method of application including angle and movement, and actual burnback technique) may result in significant performance differences. This type of assessment would require additional comparative testing and analysis to reach meaningful results.

No explicit correlation studies have been performed between small-scale burnback criteria and large-scale burnback performance. Limited data is available to perform such a correlation. The actual burnback performance differences between AFFF and other types of foam is not well established. The Navy philosophy has been to require very rapid extinguishment to meet the threat (e.g., prevent weapons cook-off), with less emphasis on burnback resistance. No explicit requirement has been established for burnback resistance (the exception is burnback performance required in shore-based hangars, which has been quantified [25]). Given the threat analysis, this philosophy continues to be appropriate.

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Table 2. Comparison Of Burnback Performance Of Various Test Standards

Test Standard	Test Preburn Time (s)	Test Pan Square/ Circular	Test Pan Size (m²)	Quantity of Agent Discharged (L)	Burnback Time (min)	Burnback Density per Minute of Burnback Protection (L/m²-min)
MIL SPEC	10	Circular	2.6	11.3	6	0.73
UL 162						
Protein-based agents	60	Square	4.6	56.7	20[1]	0.62
Film-forming agents	60	Square	4.6	37.8	14[1]	0.58
ISO/EN						
Forceful application	60	Circular	4.5	34.2	Level A – 10	0.76
Gentle application	60	Circular	4.5	57	Level B – 15	0.84
					Level C – 10	1.27
					Level D – 5	2.53
CFR/NFPA 11/O-F-555C	60	Square	9.3	113.4	20[1]	0.61
SOLAS	60	Square	4.5	57	20[2]	0.63

1   Burnback time includes "sealability" time during which the torch test is performed before the burnback test.
2   Burnback time started 5 minutes after end of agent application.

10.0   OTHER FACTORS

Protein foams and AFFF were originally developed to suppress low flash point aviation gasoline (AVGAS) and JP-4 jet fuel. The Navy has used higher flashpoint JP-5 aboard ship for many years, and the U.S. Air Force has converted to JP-8. JP-8 has similar characteristics to JP-5. Work has been performed to quantify the performance differences between low and high flash point fuels [16] and JP-5 vs. JP-8 [6,7,25].

Low flash point fuels (e.g., JP-4, gasoline) are more difficult to control and extinguish than higher flashpoint fuels. The elimination of JP-4 has improved military aviation fire protection. There are differences between JP-5 and JP-8; these differences are subtle and appear to be more pronounced under extreme conditions, e.g., when the fuel is hot or firefighting foam is diluted by water. It is unclear how these differences affect small-scale AFFF specification tests.

As noted, AFFF may not be totally effective on three-dimensional fires. Secondary agents (gaseous and powder) are provided to combat three-dimensional fires. Gravity-fed "running" fuel fires involving flight deck scenarios have been evaluated in the past [5]. This scenario included a deep-seated 35-50 gpm multi-level fuel fire with debris and simulated wing obstructions. Previous [5] and recent [26] test results indicate that this "debris pile" scenario can be successfully extinguished with AFFF handlines in zero wind conditions. There is concern that this may not represent all credible fire scenarios. There may be scenarios, not represented by the debris pile, which cannot be extinguished with AFFF alone.

11.0   CONCLUSIONS AND RECOMMENDATIONS

The systems approach is an effective method to evaluate liquid fuel hazards. For the Navy, the shipboard aircraft carrier flight deck application is one of the highest priorities for assessing firefighting agent performance. Flight deck liquid fuel hazards have a potential impact on personnel, ordnance, aircraft, and ship structures. The greatest threats are to personnel and ordnance. The potential impacts were identified: under absolute worst-case conditions (i.e., immediate immersion in flame), personnel could be seriously injured or ordnance could cook-off in less than one minute. For system analysis/design purposes, the time to reach critical thresholds for injury/damage is between 1 and 2 minutes after a liquid fuel is ignited.

To prevent the onset of critical thresholds, fire extinguishing agents must control/extinguish fires within thirty to ninety seconds. Current agents/systems meet this criteria. Agent performance characteristics could be reduced if system delivery characteristics were improved, or there was a concomitant reduction in fire threat or consequences of fire exposure, i.e., harden aircraft, increase weapons cook-off times, decreased agent delivery times, or increased system flow rates. It will be difficult to modify these existing characteristics. Agent performance in the future will likely have to meet the 30-90 second control/extinguishment performance.

There is correlation between the AFFF MIL SPEC method/criteria and large-scale pool fire extinguishment performance. The small-scale MIL SPEC method provides a factor of safety in terms of large-scale performance for AFFF agents meeting the MIL SPEC. This factor of safety is considered important during the initial application of foam to large spill fires. Overall, there may be some degree of flexibility in modifying the MIL SPEC fire extinguishment/burnback characteristics based on current threats (e.g., JP-5 fuel hazard). New agents may not be "correlatable" using the same techniques currently used for AFFF.

The MIL SPEC small-scale fire tests are considered appropriate to screen new agents. For novel agents which are not readily adaptable to the small-scale MIL SEPC fire tests, performance could be assessed at an intermediate scale. Fire control (90% extinguishment) in 30 seconds of a 1,000 ft^2 pool of low flashpoint fuel (gasoline or n-heptane) using a 50 gpm nozzle would be a reasonable screening method for aqueous foams. Any efforts to change the fire performance characteristics of the MIL SPEC should proceed with extreme caution. Reduction of safety factors carries an inherent increase in risk of degraded fire performance.

No explicit foam burnback resistance criteria have been established for large spill fires. No studies correlating small and large-scale burnback performance have been conducted. The Navy philosophy of emphasizing fire extinguishment performance in lieu of burnback performance is appropriate.

There is concern that current methods to assess three-dimensional fires may not adequately address all potential threats, particularly shielded, difficult-to-access fires in a debris field. These concerns should be addressed.

There are differences between JP-8 and JP-5 fuels in terms of extinguishment and burnback resistance. These differences are subtle and appear to be more pronounced under extreme conditions (e.g., heated fuel, heated deck, firefighting foam diluted by water).

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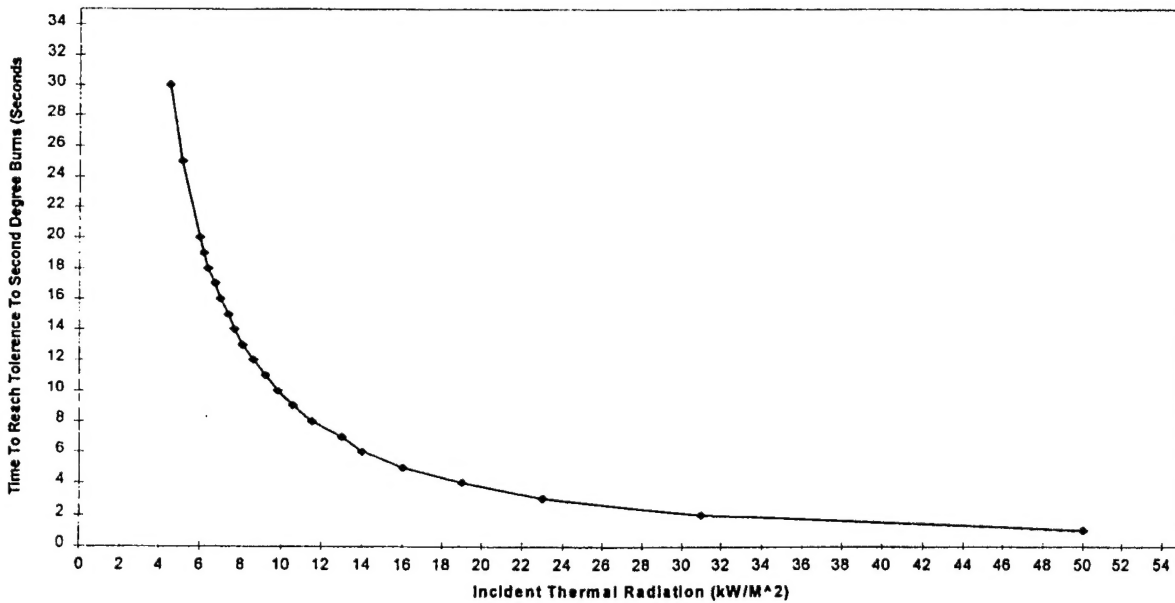
Figure 1. Time To Reach Human Tissue Tolerance to Second Degree Burns from Incident Thermal Radiation on Bare Skin
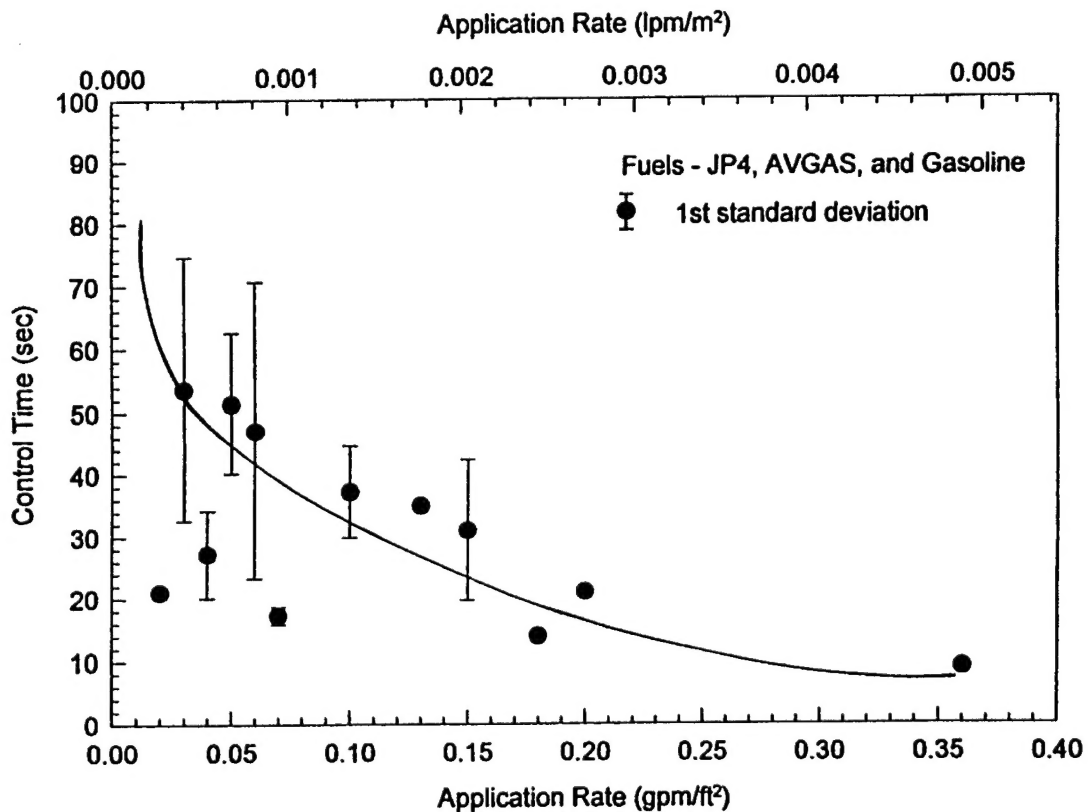

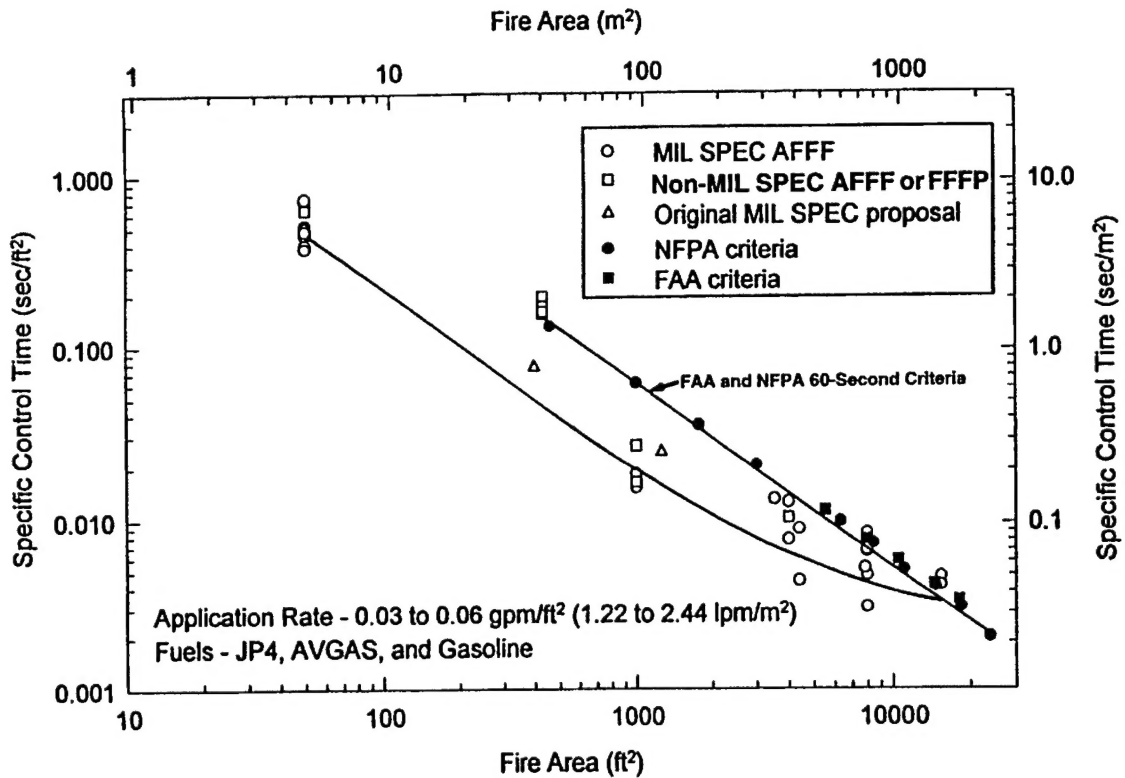**Figure 2. Effect of AFFF Application Rate on Large Pool Fires [18]**

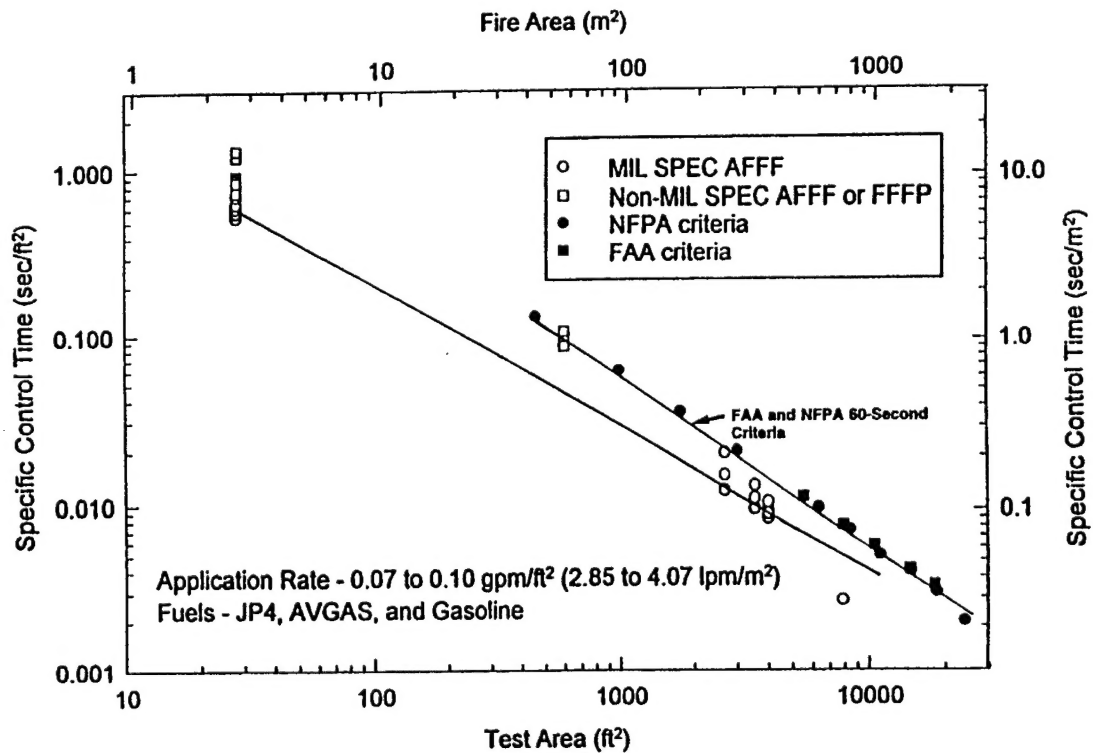**Figure 3. Specific Control Times for AFFF at Low Application Rates [18]**

Figure 4. Specific Control Times for AFFF at Intermediate Application Rates [18]